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RECIPROCATING SLIDING WEAR CHARACTERISTICS OF COPPER-CARBON FIBER COMPOSITES

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16. Abstract

The effect of fiber arrangements and alloy compn. on the reciprocating sliding wear behavior of Cu-C fiber composite was studied. The wear vol. was smaller than that of Cu alloys. The wear vol. increased with increasing sliding load and vol. fraction of C fibers above 30 vol. %. The effectiveness of fiber arrangement in decreasing the wear vol. was the highest for the random arrangement, medium in the direction perpendicular to the fiber direction, and lowest in the fiber direction. The wear vol. was decreased by the addn. of Sn and Zr. However, the addns. did not achieve isotropic wear characteristics of the composite. Isotropic wear was obtained by the addn. of C powder. Isotropic wear and decreased wear of the composite were attained by adding Zr and C powder together.

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RECIPROCATING SLIDING WEAR CHARACTERISTICS OF COPPER-CARBON FIBER COMPOSITES*

***/119

Keiichi Kuniya**, Hideo Arakawa** and Takashi Namekawa**

The effect of fiber arrangements and additional elements on reciprocating sliding wear characteristics of copper-carbon fiber composite was studied. Results obtained in this study were as follows:

1) The wear volume of the copper-carbon fiber composite appeared to be smaller than that of copper alloys.

2) The wear volume of the copper-carbon fiber composite became larger, as the sliding load increased and the volume fraction of carbon fiber increased beyond 30 volume percent.

3) The effectiveness of fiber arrangement in reducing the wear volume was the highest in the random arrangement, medium in the direction perpendicular to the unidirectional fiber direction and the lowest in this fiber direction.

4) The wear volume of the composite was decreased by the addition of Sn and Zr. However, the addition of these elements could not achieve the isotropic wear characteristics of the composite.

5) It was found that the isotropic wear characteristics of the composite could be obtained by the addition of carbon powder. The isotropic wear characteristics and the reducing wear volume of the composite could be attained by the addition of Zr and carbon powder together.

Received July 23, 1982

Keywords: carbon fiber, copper-carbon composite, fiber reinforced metal, wear characteristics, additional element

I. Introduction

It has been well known that mixtures of metals and carbon powder have excellent wear characteristics, and such mixtures in industry are made mainly by powder metallurgical means. This method is subject to restrictions in terms of dimension, shape and strength, so that recently production of graphite dispersed alloy by the casting method has been tried [1]. However, when powder is used in various electric parts, characteristics that become necessary such as low thermal expansion could not be obtained.

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*** Nos. in margin indicate pagination of foreign text.

It has already been reported that in copper-carbon fiber composites in which copper is reinforced with carbon fibers (hereinafter referred to as Cu-C fiber composites), the desired characteristics such as thermal expansion coefficients, Young's rates, thermal conduction rates, and electric conduction rates, could be obtained by selecting the types, orientation and contents of fibers [2-7]. Thus, wear characteristics of Cu-C fiber composites were studied.

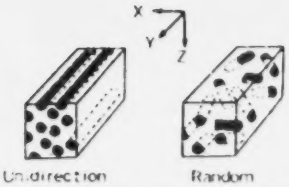
Several studies have been reported on wear characteristics of fiber composites [8-16], but no systematic studies have been made. The present study covered the effects of fiber orientation on wear characteristics, the addition of carbon powder in order to eliminate the anisotropy of wear characteristics, and reinforcement of fiber-matrix interface by adding Zr, which are basic properties of wear characteristics of Cu-C fiber composites.

II. Experimental method

1. Material and method of constructing specimens

The material used include carbon fibers and powdered Cu, Sn, Zr and carbon. In order to distinguish from carbon fibers, carbon powder will be referred to as Cp. Carbon fiber is a high strength fiber of the PAN type, Cu is an electrolytic powder with a granular diameter of 5 μm, and Sn, Zr and Cp had granular diameters of 3.8 μm, 2.2 μm and 1 μm.

As shown in Figure 1, specimens used in the experiments were mainly unidirectional composites, to which various elements (powdered Sn, Zr and Cp) were added. Also, for comparison, short fiber random composites were constructed. These random composites had their fibers oriented during hot pressing so that a state close to 2-dimensional random orientation was attained.



No.	Kinds of composite	Content of fiber vol%	Content of additives (vol%)	Test condition: Sliding direction / Fiber orientation
1	Random Cu-C	50	—	A (X, Z)
2	Unidirection			B (X)
3	Cu-C			C (Y)
4				D (X, Z)
5		40		D
6		30		
7		20		
8	Cu-Sn-C	30	8 Sn	
9		50	6 Sn	D
10	Cu-Zr-C	50	10 Zr	
11				B
12	Cu-Cp-C	30	17 Cp	D
13				B
14	Cu-Zr-Cp-C	30	10 Zr + 17 Cp	D
15				B

Figure 1. Details of composites and test conditions for dry friction.

The method of specimen construction is as follows. To carbon fibers about 1 μm thick layer of copper is plated, and for unidirectional composites, they were wound around equidistantly on spool-shaped jigs, then sliced to make preformed sheets. In random composites, copper plated fibers were cut into 5-10 mm lengths, and agitated in water to construct short fiber collective bodies.

Powdered Cu and powdered element X to be added (Sn, Zr, Cp) were stirred in 3% aqueous solution of methylcellulose to make

Cu-X or X powder slurries, which were impregnated in the fiber preparations mentioned above. The resulting specimens were dried and solidified under atmospheric pressure at 373 K, and were hot pressed under N_2 + 8 vol % H_2 atmosphere, at 1273 K, 1.2 ks (20 min), 24.5 MPa.

2. Method of testing for wear

The testing for wear was carried out under atmospheric pressure with dry friction, using a reciprocating sliding wear testing apparatus. The load was placed on the stationary side specimen in which Cu-C fiber composite of 7 mm diameter and 10 mm length was soldered on to a copper base. On this specimen, mobile side specimen, 10mmx 12 mm x 85 mm (S45 C), was made to slide reciprocally. The testing conditions were surface pressure 0.69-4.9 MPa, the number of reciprocal slipping 0.73 time/s (average sliding speed 0.088 m/s).

For the testing, as shown in Figure 1, the sliding surface and angle of sliding of unidirectional composite are of three types, namely X direction to fiber cross section (or Z direction), X direction to the side of the fiber (direction of the fiber and sliding are at right angle), and Y direction (directions of fiber and sliding are parallel). These were designated as wear methods D, B and C respectively. The direction of sliding of the short fiber randomly oriented composites are almost equal for X, Y and Z directions, and this was designated as wear method A.

After reciprocal sliding, the amounts of wear of Cu-C fiber composites and the corresponding sliding surface of the mobile material (S45C) were measured in relation with sliding distance. Also, the worn surfaces were observed with optic and scanning electron microscopes.

Also, wear resistant copper alloys such as bronze alloy (Cu-9 mass % Sn-5 mass % Zn), phosphorus bronze alloy (Cu-13

mass % Sn-0.3 mass % P) and high power brass alloy (Cu-5 mass % Al-3 mass % Fe-4 mass % Mn-25 mass % Zn) were tested under the same conditions as for Cu-C fiber composites, and the amounts of wear were compared.

III. Experimental results and discussion

1. Comparison of Cu-C fiber composites and wear-resistant copper alloys

Figure 2 shows the comparison of wear characteristics of various wear-resistant copper alloys and Cu-C fiber composites (specimen 4, unidirectional Cu-50 vol %, C-material cross section). Each specimen showed a linear increase of the amount of wear with an increase in the distance of sliding. The amount of wear was the greatest in bronze alloy followed by those of phosphorus bronze, and high power brass alloy, with a minimum noted in the unidirectional Cu-50 vol % C material cross section.

Figure 3 shows the relationship between the amount of wear and pressure on the wear testing surface of specimen 4. The wear data of the high power brass alloy (surface pressure 0.69 MPa) were also shown for comparison. The amount of wear of specimen 4 increases with an increase in surface pressure. However, its wear was less than that of the high power brass alloy, which showed the least wear among the wear-resistant copper alloys, even on the surface pressure of 4.9 MPa. Thus, it was noted that Cu-C fiber composites had less wear and better wear characteristics in comparison with wear-resistant copper alloys in general use.

2. Effects of the amounts and orientation of fibers on wear characteristics

Figure 4 shows the relationship between the amount of wear, the amount of fiber fibers and the sliding distance of cross-sections of unidirectional composite specimens (nos. 3, 4, 5, 6

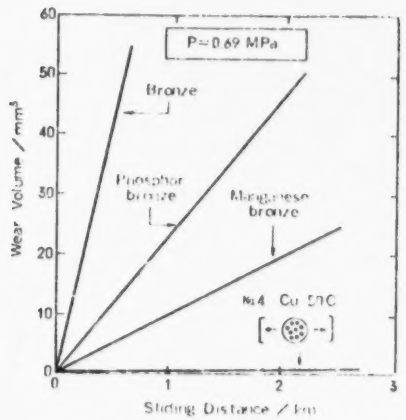


Figure 2. Comparison of copper alloys with Cu-C fiber composite in wear volume and sliding distance.

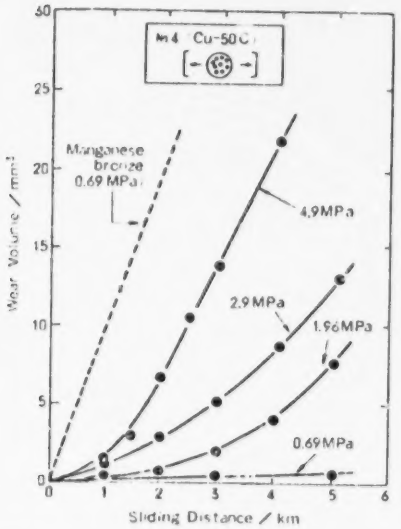


Figure 3. Effect of load and sliding distance on wear volume of Cu-C composite containing 50% volume fraction of fiber.

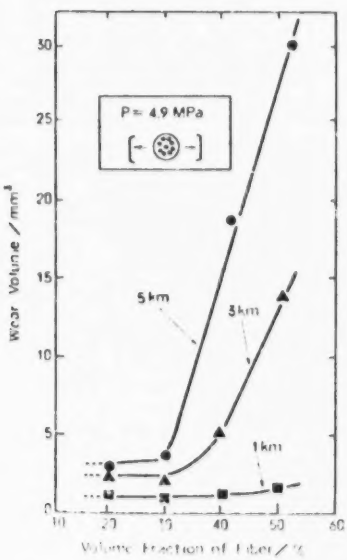


Figure 4. Wear volume vs. volume fraction of fiber in Cu-C fiber composites.

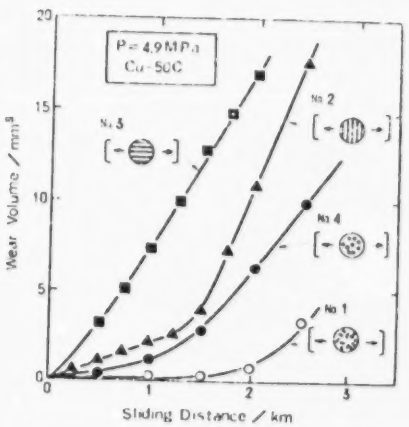


Figure 5. Effect of sliding direction and fiber arrangement on wear volume of Cu-C composite containing 50% volume fraction of fiber.

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TABLE 1. Effect of fiber arrangements and test conditions on wear volume of counter material (S45C) under a load of 4.9 MPa after 2.5 km sliding distance.

No.	Fiber arrangement	Test condition	Wear volume of counter material (mg)
1	Random	A	12.5
2	Unidirection	B	92.0
3		C	78.0
4		D	59.8

and 7). The amount of wear was constant when the amount of carbon fiber was 30-40% or less, but above this range, rapid increases were noted with an increase in the amount of fibers. Also, the amount of wear increased with an increase in the sliding distance.

Figure 5 shows the relationship between the amounts of wear and fiber orientation, the sliding surface and sliding direction, in unilateral (nos. 2-4) and random orientation (no. 1) composites containing 50 vol % carbon fiber. All specimens failed to show constant wear and the amounts of wear increased with an increase in the sliding distance. The greatest amount of wear was noted in specimen 3, followed by 2, 4, with the minimum in 1.

Table 1 shows the amounts of wear of the counter material (S45C). This material also showed wear characteristics similar to those in Cu-C fiber composites. The wear was minimum when it was matched against random orientation composites, followed by unidirectional composite cross section, and became maximum when matched against the side.

Figure 6 shows optical photomicrographs of sliding surfaces of various Cu-50 vol % C composites before and after wear testing. Each specimen showed some damage where carbon fibers and the copper matrix exfoliated and dropped. Also after testing, their sliding surface showed coagulated gray layers.

Figure 7 shows scanning radiographics of damaged areas of sliding surfaces of specimens 1, 2 and 4, obtained by the scanning electron microscope system (SEM system) and X-ray

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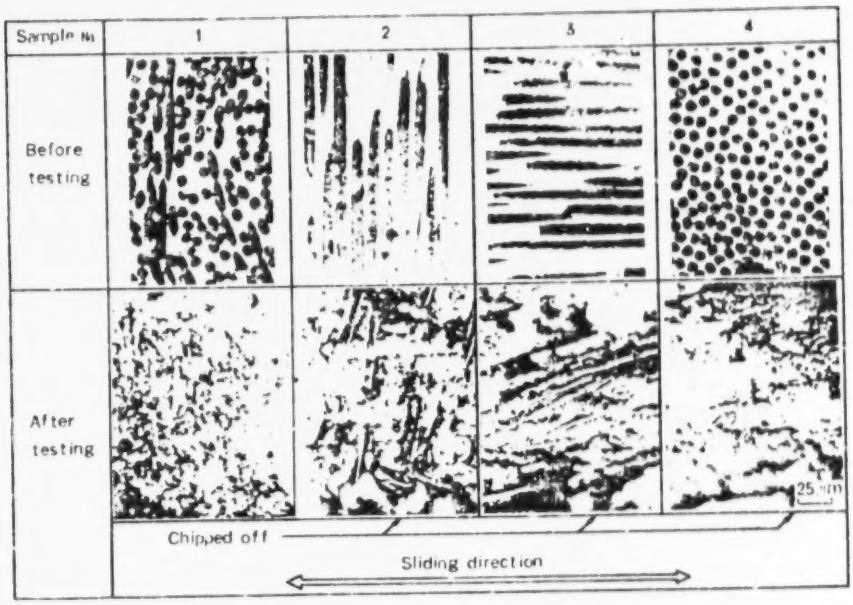

Figure 6. Microphotographs of surfaces before and after dry friction of Cu-C composites containing 50% volume fraction of fiber. (load: 4.9 MPa, sliding distance: 2.5 km)

microanalyzer (EPMA). The damaged portion of specimen 2 showed exposed carbon fibers as well as broken fibers and evidence of fiber exfoliation. From the results of EPMA, it could be seen that spots of Fe were present on copper matrix surfaces. The damaged portion of specimen 4 showed broken fibers and coagulation of Fe, as well as in specimen 2, but the amount of Fe was less. Coagulation of Fe was clearly noted in specimen 1. The Fe came from the counter material. Also, as in specimens 2 and 4, breakage and exfoliation of fibers were noted.

The carbon fiber is a layered graphite crystal (hexahedral system). The wear of the fiber itself progresses with layered wear of the graphite crystals. Thus, in general, it is thought that the wear of carbon fiber reinforces is mild under self-lubrication [8]. The sides of carbon fibers mainly consist of sliding surfaces of hexahedron system (0001) [17]. If the carbon fiber itself had a self-lubricating effect, powder from carbon

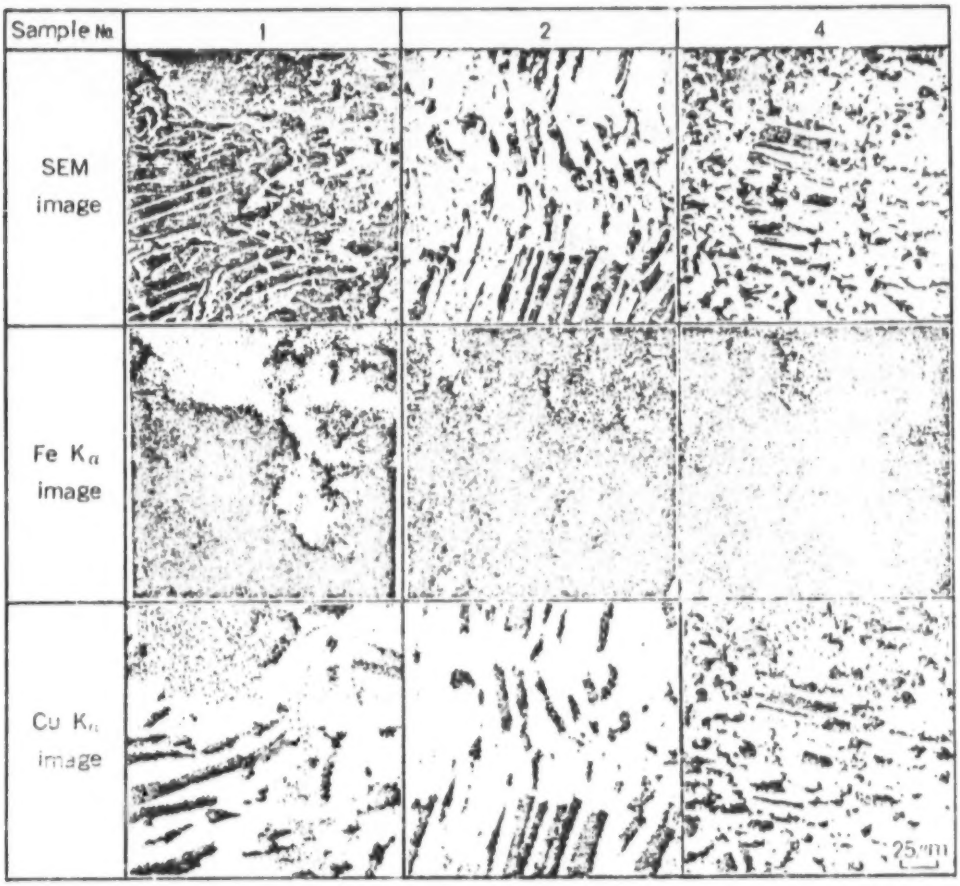

Figure 7. EPMA analysis of worn surface of Cu-C composites containing 50% volume fraction of fiber. (Load: 4.9 MPa, sliding distance: 2.5 km)

fibers wearing is more readily formed when sliding occurs on the side of the fiber. Thus, specimens 3 and 2 in which the side of fibers form sliding surfaces should have less wear than that of specimen 4 in which sliding occurs on the cross section. Similarly, in contrast to that shown in Figure 4, the amount of wear should be less with greater carbon fiber contents.

The experimental results contrary to these predictions were obtained and are thought to be due to the following factors.

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Copper and carbon do not have wetting properties [18] and they do not mold or react [19]. Accordingly, the bonding between carbon fibers and the copper matrix is achieved only through the force of electrocoagulation and mechanical adhesion force due to the irregularity of the carbon fiber surface. Thus, the force of bonding at the fiber-matrix interface is small. Because of this, in reciprocal sliding tests under relatively high loads, as in the present study, breakage, exfoliation and dropping lead to damages on sliding surfaces, and further damages occur due to adhesion of Fe from the counter material, which causes an increase in friction in that portion. Frequent repetition of these events are thought to have caused the increase in the amount, of wear with an increase in the sliding distance, as shown in Figure 5. The increase in amounts of wear with an increase in the amount of fibers, as shown in Figure 4, is thought to be due to the same causes; that is, the force of bonding at the fiber-matrix interface is small, excessive fibers lead to more exfoliation of fibers, resulting in an increase in the amount of wear.

Similarly, because of tne weakness of the bonding force at the fiber-matrix interface when sides of fibers were the sliding surface (nos. 2 and 3), the sliding caused fiber exfoliation more readily, resulting in more wear than when the cross section of fibers was the sliding surface (no. 4). Also, it is thought that the reason that the amount of wear of the random orientation composite (no. 1) was less than that of no. 4, in which the cross section was the sliding surface, was that with the random orientation composite, fibers were bent and embedded in matrix [4], thus lessening fiber exfoliation and, as noted above, the self-lubricating effects of wear powder from the side of fibers worked favorably.

3. Effects of Sn, Zr and carbon powder on wear characteristics

The methods to improve wear characteristics of Cu-C fiber

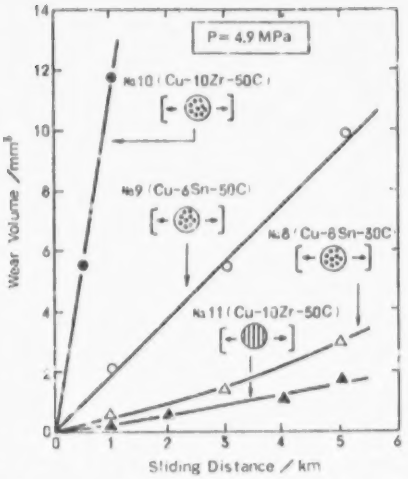

Figure 8. Effect of sliding surface, fiber content and addition of Sn and Zr on wear volume of Cu-C fiber composites.

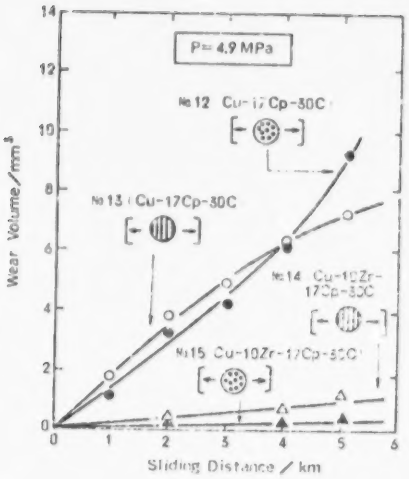

Figure 9. Effect of sliding surface and addition of Zr and carbon powder on wear volume of Cu-C fiber composites.

composites include: (1) wear instance of the copper matrix is improved by the addition of Sn, (2) carbide layer is formed on the surface of carbon fibers by the addition of a carbide-forming element Zr, and through that layer stray bondings of copper and matrix is obtained, or (3) reducing anisotropy of wear characteristics by the addition of graphite powder. Effects of these added elements are discussed below.

Figure 8 shows the amounts of wear of specimens nos. 8 and 9 to which Sn was added, and nos. 10 and 11, to which Zr was added. As could be seen, the addition of Sn causes reduction in the amounts of wear, but its extent is small. When the volume of carbon fiber reached 50 vol %, the amount of wear increased, compared to when it was 30 vol %. The same tendency was noted when Sn was not added. When Zr is added, the amount of wear decreased markedly in specimen 11, in which the side of fibers form a sliding surface, but no reducing effect was noted when the cross section was the sliding surface (10).

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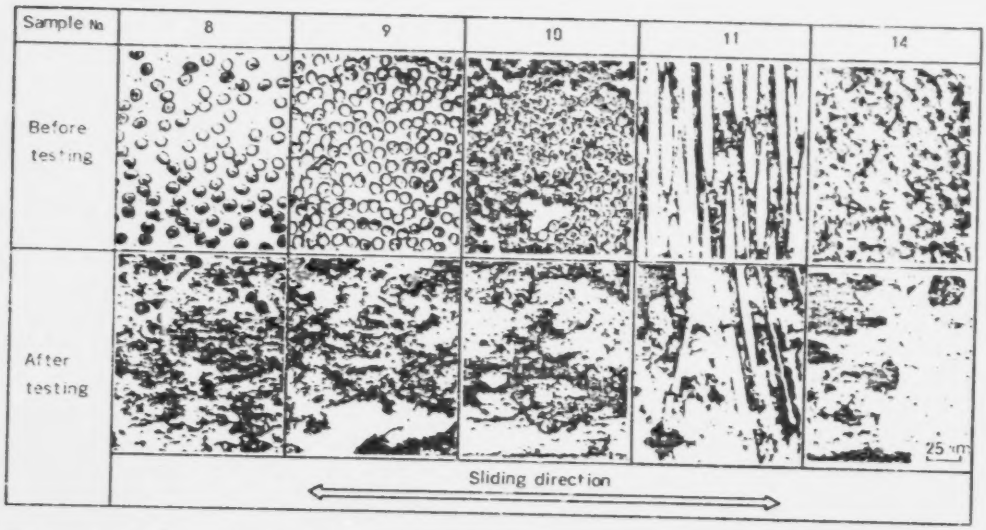

Figure 10. Microphotographs of surfaces before and after dry friction of Cu-C fiber composites containing Sn, Zr and C powders. (Load: 4.9 MPa, sliding distance: 5 km)

Figure 9 shows the amounts of wear in nos. 12 and 13, to which carbon powder was added, and nos. 14 and 15, to which Zr and carbon powders were added. As could be seen from the figure, the addition of carbon powder eliminated the anisotropy of the wear characteristics due to the sliding surfaces, resulting in about equal degree of amounts of wear in nos. 12 and 13. The addition of carbon powder eliminates the anisotropy due to the sliding surfaces so that further addition of Zr, as noted above, to reinforce the fiber-matrix interface, as noted in nos. 14 and 15, resulted in a marked reduction of the amounts of wear and, in addition, virtually no anisotropy of wear characteristics was noted.

Figure 10 shows photomicrographs of sliding surfaces of specimens 8-11 and 14. Relatively smooth sliding surface with fiber cross section exposed could be seen in 8, but in 9, fiber cross section is nonrecognizable due to adhesion of the counter material. The addition of Sn improves wear resistance of copper

matrix, but the force of the bonding at fiber-matrix interface is not strengthened. Accordingly, as noted above, when the volume of fibers became excessive, the fibers that break and exfoliate also increase, increasing the amount of wear of the composite, reducing self-lubricating effects of carbon fiber, scratch wear is also produced, resulting in an increase of the amount of wear of the counter material and of adhesion.

Specimen 10 to which Zr was added, and cross section formed the sliding surface, shows adhesion of the counter material on the sliding surface. In contrast, the side of fibers in 11 shows exposed fibers, and no exfoliation of fibers is noted, as in 8. As previously reported [4], when a layer of Zr carbide is formed on the surface of carbon fibers by the addition of Zr, the strength of the fiber-matrix interface increases, preventing fiber exfoliation, leading to the significant decrease of the amount of wear in specimen 11, in which the side of fibers with high self-lubricating effect of carbon fibers, was used as the sliding surface. The photomicrograph of the sliding surface of specimen 14 shows the presence of carbon powder in the copper matrix.

From the foregoing, it was noted that when carbon forming elements such as Zr was added to achieve a strong bonding of carbon fiber and copper matrix, exfoliation and dropping of carbon fibers were prevented, and wear resistance characteristics of Cu-C fiber composite were improved. It was also noted that the addition of carbon powder eliminated the anisotropy of wear characteristics.

IV. Conclusion

The reciprocating sliding wear characteristics of Cu-C fiber composites were studied, and the following findings were obtained.

(1) Cu-C fiber composites have better wear resistance

characteristics than wear-resistant copper alloys.

(2) The amount of wear increases with an increase in pressure of the sliding surface. When the volume of fiber exceeds 30-40 vol %, the amount of wear increases in proportion with an increase in fiber volume, due to the small interface strength of carbon fiber-copper matrix which facilitate exfoliation and dropping of fibers, increasing the apparent amount of wear.

(3) The amount of wear of Cu-C fiber composites was minimum with short fiber random orientation, and increase in order of unilaterally oriented fiber cross section, and fiber side. The amount of wear in random orientation is small because exfoliation and dropping of fiber is difficult to occur, and the side of fibers, where carbon powder is easily generated, act as the sliding surface.

(4) The amount of wear decreases when Sn is added to achieve wear resistance of the matrix. When the force of bonding between the fiber and the matrix is strengthened by the addition of Zr, fiber exfoliation and dropping are eliminated, resulting in a significant decrease of the amount of wear. However, the anisotropy of wear characteristics due to the difference in sliding surfaces could not be eliminated.

(5) When carbon powder is added, the anisotropy of wear characteristics due to the difference in sliding surfaces is eliminated. When carbon and Zr powders are added, the exfoliation and dropping of fibers are prevented, and wear characteristics without anisotropy due to the sliding surface are obtained.

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